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Preface

The Space Programs Summary is a six-volume bimonthly publication designed to report on JPL space exploration programs and related supporting research and advanced development projects. The titles of all volumes of the Space Programs Summary are:

Vol. I. *The Lunar Program* (Confidential)
Vol. II. *The Planetary–Interplanetary Program* (Confidential)
Vol. III. *The Deep Space Network* (Unclassified)
Vol. IV. *Supporting Research and Advanced Development* (Unclassified)
Vol. V. *Supporting Research and Advanced Development* (Confidential)
Vol. VI. *Space Exploration Programs and Space Sciences* (Unclassified)

The Space Programs Summary, Vol. VI, consists of an unclassified digest of appropriate material from Vols. I, II, and III; an original presentation of the JPL quality assurance and reliability efforts, and the environmental- and dynamic-testing facility-development activities; and a reprint of the space science instrumentation studies of Vols. I and II.

Approved by:

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I. Liquid Propulsion

PROPULSION DIVISION

A. Injector Development, *R. W. Riebling*

1. Introduction

One objective of the JPL Injector Development Program is the development of a restartable spacecraft rocket engine injector in the 2000 to 4000 lb_f thrust class. This injector must have a high combustion efficiency (at least 95% of the theoretically attainable shifting equilibrium characteristic velocity, c^*), and be continuously throttlable over at least a 10-to-1 thrust ratio without significant loss in that efficiency. In addition, it must provide a predictable heat transfer environment compatible with chamber and nozzle wall materials. The propellants are nitrogen tetroxide (N_2O_4) and hydrazine (N_2H_4) at a nominal mixture ratio of 1.2 and a full-thrust chamber pressure of 150 psia.

As a first step toward the fulfillment of these requirements, a 78-element, 2000-lb_f thrust (at altitude) heavyweight injector was designed and fabricated to: (1) demonstrate the feasibility of JPL's "impinging-sheet" injection concept in multi-element configurations, (2) evaluate several promising candidate throttling techniques, and (3) generate design criteria for future flightweight models. The injector was described earlier (SPS 37-41, Vol. V, p. 7).

One of the throttling techniques investigated was the so-called "pressure/area-step" method, described in the cited SPS. When the 78-element, impinging-sheet injector was throttled using this scheme, combustion efficiencies, η_{c^*} of about 98.5% were realized at full thrust, and nearly 4-to-1 throttling was accomplished before η_{c^*} decreased to 95%. While this was a significant achievement in itself, the results still fell short of meeting the program objective of a full 10-to-1 throttling capability at c^* efficiencies in excess of 95%. Accordingly, a second throttling method, known as the "discrete-element" technique, was studied. The latter method did show a potential capability of yielding c^* efficiencies of 95% or greater over the entire 10-to-1 throttle range, and it thus might be one way in which the program objectives can be met. This report will describe the discrete-element throttling method, and will present and discuss the results of the test firings which demonstrate its 10-to-1 potential.

2. Discrete-Element Throttling

In this technique, still in the conceptual stage, no propellant manifolds *per se* would be used. Instead, each individual fuel orifice would be connected directly to the fuel throttle valve by means of its own feeder tube. The

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valve would be constructed in such a way that it could shut off discrete fuel orifices one at a time (or several at a time, if desired). Similarly, each oxidizer orifice would be fed directly by the oxidizer throttle valve. The valves would be mechanically linked and the combination driven by a single actuator. Throttling would be accomplished by the valve's progressively opening (or closing) the entrances to the individual feeder tubes, thus turning on (or shutting off) discrete injection elements singly or in groups. Each element would be either full *on* or full *off*. If supply pressure were held constant, injection pressure drops would *increase* as flow rates were reduced by the change in total orifice area.

The successful implementation of this concept requires the use of an injection element which is inherently so efficient that it does not depend strongly on interactions between its own spray and the sprays produced by its neighbors for efficient propellant mixing and combustion. Only in this way can performance degradation be avoided under deep-throttled conditions when only a few relatively-isolated injection elements remain on. One such element is JPL's unlike impinging-sheet device. Previous work (SPS 37-35, Vol. IV, p. 152) showed that single impinging-sheet elements could deliver c^* efficiencies in excess of 95% over a wide range of injection velocities with the N_2O_4/N_2H_4 propellant combination. A second requirement, of course, is that a suitable valve, which can perform the discrete-orifice throttling, be available. Such a valve, incorporating both the on-off and throttling functions, is being developed concurrently at JPL. Its design was described in Ref. 1, and a future SPS will present the results of its experimental evaluation.

3. Test Conditions

Thirteen short-duration firings were made with N_2O_4/N_2H_4 propellants to evaluate the performance delivered by the 78-element, impinging-sheet injector when throttled by the discrete-element technique. To conserve costs, continuous throttling was not employed for these feasibility demonstrations. Instead, a series of "fixed-point" tests were conducted, in which the steady-state total propellant flow rate remained constant during each individual test, but varied from one test to the next.

Discrete-element throttling was simulated by closing off the entrances to various orifice feeder tubes by inserting Teflon plugs. In this manner, effective injector patterns consisting of 27, 18, 13, 8, and 3 elements were obtained; these are shown in Fig. 1(c) through (g). Several firings were made with each injector pattern, in order to assess the effects on c^* efficiency of varying chamber pressure and injection velocity. From the data obtained in this series of firings, as well as that collected earlier (SPS 37-41, Vol. V) with the 42- and 78-element configurations (Figs. 1a and 1b), it was possible to synthesize curves of the key performance parameters vs the throttle ratio, ϕ.

All firings were conducted in an uncooled "workhorse" combustion chamber having a characteristic length L^* of 39 in. Its geometry was summarized in SPS 37-41, Vol. V. This chamber was instrumented with thermocouple plugs for heat flux measurements and, during "sea-level" firings, with flush-mounted, high-frequency-response pressure transducers[1] to monitor combustion stability. It was not feasible to install "Photocons" on those tests conducted in the vacuum chamber, but no instabilities were expected due to the very low chamber pressures in those tests.

Approximately half the firings were conducted at an ambient pressure of about 13.5 psia with an expansion area ratio of 2.43. The remainder (those at the lower chamber pressures) were made with the same thrust chamber in the Edwards Test Station (ETS) altitude facility to assure that the nozzle would flow sonic without separation during deep-throttled firings. In order to avoid any possibility of ignition overpressures, or "spiking," the altitude firings were started at an intermediate pressure level (about 3 to 4 psia). Upon ignition, the vacuum chamber was quickly exhausted to the altitiude conditions (0.1 to 0.5 psia, depending on engine flow rate) under which the steady-state data were recorded. It must be pointed out, however, that this technique was only a convenient "fix" to facilitate smooth starts in the present experiments. When started under hard vacuum, this engine exhibited the high transient overpressures ("spikes") typical of the altitude ignition of this class of propellants.

4. Experimental Results

The performance results are summarized in Table 1. The durations reported are steady-state values. The use of the uncooled thrust chamber and the low-conductivity steel deflectors made short firing durations mandatory. The chamber pressures reported are stagnation values at the entrance to the converging portion of the nozzle, and were obtained from the measured values by applying the

[1] Model 307, Photocon Research Products, Pasadena, California.

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Fig. 1. Discrete element throttling, showing mass distribution patterns near injector face with various numbers of elements flowing (artist's conception)

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Table 1. Summary of performance results

Test No.	No. of elements firing	Duration, sec	Oxidizer/ fuel mixture ratio, r	Chamber stagnation pressure p_c, psia	Oxidizer injection pressure drop, psid	Total flow rate, $\dot{w}_t$, lb_m/sec	Measured thrust F, lb_f	Characteristic velocity c*, ft/sec	Characteristic velocity efficiency η_{c^*}, %
19	27	3.5	1.19	83	170	3.61	698	5660	97.7
20	27	3.5	1.19	67	111	2.90	528	5670	98.0
21	27	2.5	1.22	49	68	2.21	345	5490	95.3
22	27	2.5	1.22	47	64	2.15	331	5420	94.2
23	27	4.0	1.16	39	41	1.74	268	5550	96.3
24	18	3.0	1.20	56	164	2.45	390	5600	97.0
25	18	4.0	1.12	32	57	1.37	—[a]	5660	98.0
26	13	3.0	1.19	40	177	1.79	301	5500	96.3
27	13	4.5	1.17	24	64	1.09	—[a]	5500	95.7
28	8	5.0	1.13	25	195	1.13	—[a]	5510	96.0
29	8	5.5	1.14	15	66	0.691	—[a]	5416	94.4
30	3	6.5	1.24	9	211	0.455	—[a]	4831	—[b]
31	3	8.0	2.24	4	74	0.2	—[a]	4914	—[b]

[a] Not measured; altitude cell thrust mount not available at Edwards Test Station.

[b] Reliable theoretical performance data not available.

standard static-to-stagnation correction. No other corrections have been made to the reported values of c^*. These are included mainly for comparative purposes, and were calculated by comparing the uncorrected measured values to the theoretical full shifting equilibrium values at the experimental chamber pressures and mixture ratios. When extant methods of correcting for heat loss, throat area change and radius of curvature, nozzle discharge coefficient, and frictional drag losses were applied to the data to obtain a rough estimate of the magnitude of the total correction to c^*, it was found that they combined in such a way as to introduce only negligible changes in the reported values.

The values of thrust reported are those measured in the firings conducted at ambient pressure (approximately 13.5 psia) with an expansion area ratio of 2.43. Superscript *a* in Table 1 indicates firings made with the same thrust chamber in the ETS altitude facility. Unfortunately, a thrust mount suitable for use with the 2K engine assembly and compatible with the vacuum chamber was not available during testing, so thrust was not measured for the altitude firings.

Table 1 also contains measured values of the oxidizer injection pressure drop, since these will be involved in the discussion that follows. Fuel pressure drops were nearly equal to the oxidizer drops in all tests, as intended in the original design.

The chamber pressure in the two 3-element firings (Tests 30 and 31) was below the vapor pressure of nitrogen tetroxide at injection conditions. It would be expected that some degree of oxidizer flashing would occur under these circumstances, and that the resulting 2-phase (or vapor) flow would adversely affect the degree of propellant mixing and atomization attainable. Examination of the high-speed motion pictures made during these two tests showed large droplets of unburned hydrazine emerging from the nozzle, and this is in agreement with incomplete mixing due to gasification of the oxidizer, as postulated above. For these reasons, it was felt that the results of Tests 30 and 31 could not properly be compared with those of the other firings on an equal basis. In the following discussion, no further consideration will be given the 3-element firings.

Because of the short firing durations used as a precaution against damaging the steel deflectors, the thrust chamber walls and throat did not reach temperatures in excess of 300°F and 800°F, respectively. In most cases, the maximum temperatures were even lower, and this

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limited thermal response was not sufficient to permit accurate calculation of local heat flux and gas side film coefficients for the firings reported in Table 1. Heat flux measurements for this injector firing at higher chamber pressures were reported in SPS 37-41, Vol. V.

As noted in the higher chamber pressure firings reported in the cited SPS, the deflectors of those elements which had been totally shut off sustained varying degrees of localized burning or erosion. However, not all were rendered completely unserviceable this time, undoubtedly because of the relatively milder convective environments prevailing at reduced chamber pressures. Nevertheless, these tests again pointed out the potential problem areas associated with exposed elements, and future versions of this injector are being fabricated with deflectors recessed flush with the injector face.

Very smooth combustion was encountered in all firings. The "combustion roughness parameter," $\Delta P_c/P_c$, did not exceed 2%; ΔP_c is the root-mean-square amplitude of high-frequency chamber pressure oscillations (see Table 2 for definitions of symbols).

Table 2. Definition of terms

A	throat area, in.^{2}
c^*	characteristic velocity, ft/sec
F	thrust (measured), lbf
L^*	characteristic chamber length, in.
P	stagnation pressure, psia
r	mixture ratio, oxidizer/fuel
$\dot{w}$	flow rate, lb/sec
η	efficiency, %
ϕ	throttle ratio
Subscripts	
a	ambient
c	chamber (combustion)
m	mass, lb
o	stagnation
t	total
w	wall

5. Discussion of Results

Total flow rate, oxidizer injection pressure drop, chamber pressure, and c^* efficiency are plotted versus the throttle ratio ϕ in Fig. 2 for those tests (24, 26, 28, and 30) in which discrete-orifice throttling was carried out at a constant supply pressure of 220 psia (both fuel and oxidizer). The points shown for the 27- and 42-element configurations were obtained by interpolation from the 27-element firings (Table 1) and the 42-element firings reported in SPS 37-41, Vol. V. These graphs may be used to illustrate how those key parameters vary when the engine is throttled by the discrete-element method at constant supply pressure. The throttle ratio ϕ is defined as the total weight flow rate at maximum thrust (in this case, 6.54 lb_m/sec for an altitude thrust of 2000 lb_f at an expansion area ratio of 40:1) divided by the total weight flow rate measured in a particular test. This ratio, ϕ, is numerically very close to the corresponding ratio of maximum altitude thrust (2000 lb_f) to the altitude thrust calculated for each test from the relation,

$$F = c_f P_c A_t \qquad (1)$$

taking c_f constant at the calculated value of 1.75(ϵ=40:1). In this report, however, ϕ has been defined in terms of weight flows so that the throttle ratios may be derived

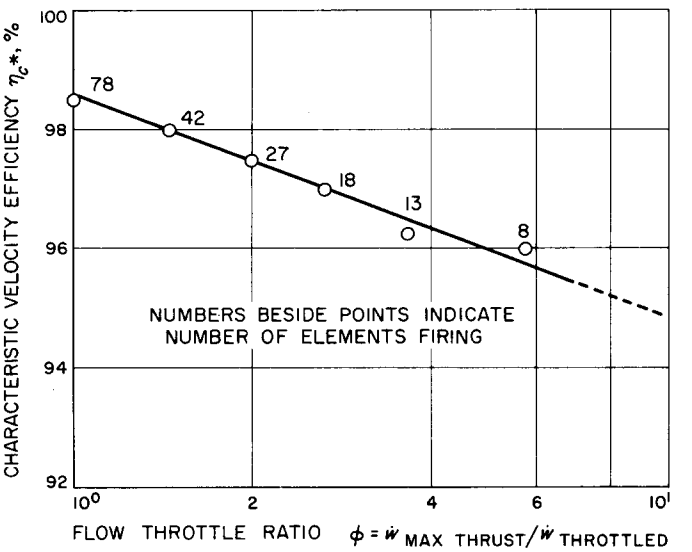

Fig. 2. Variation of c* efficiency during discrete-element throttling of 78-element impinging-sheet injector at constant supply pressure of 220 psia

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from actually-measured, rather than calculated, values. The numbers next to the data points indicate how many elements were fired in each case. For the pattern arrangements, refer to Fig. 1.

Examination of Fig. 2 will show that c^* efficiencies of about 98.5% were realized at full thrust (78 elements firing, throttle ratio of 1.0), and that these declined gradually to 96% at a throttle ratio of 5.75. Extrapolation of the curve of Fig. 2 indicates that throttling could probably be continued all the way to $\phi = 10$ without η_{c^*} falling below about 95%. Chamber pressure decreased almost linearly with total flow rate since combustion efficiency was almost constant (Fig. 3). Injection pressure drops increased with throttling, as shown in Fig. 4, asymptotically approaching the supply pressure. The number of elements firing vs ϕ is plotted as a matter of convenience in Fig. 5. Extrapolation of the curve of Fig. 5 indicates that throttling by as much as 10-to-1 could probably be accomplished in this case by shutting off all but 4 or 5 of the original 78 elements. Firings with 4 and 5 elements will be made to verify this contention.

Perhaps the most striking advantage of discrete-element throttling is the extremely wide range over which throttling can be accomplished at high and nearly constant performance efficiencies. Indeed, it would seem that the premature vaporization of oxidizer at low chamber pressures may be the only factor limiting the attainable throttle range. If that were true, 10-to-1 would be about as far as any engine designed for N_2O_4/N_2H_4 at a maximum chamber pressure of 150 psia could ever be throttled.

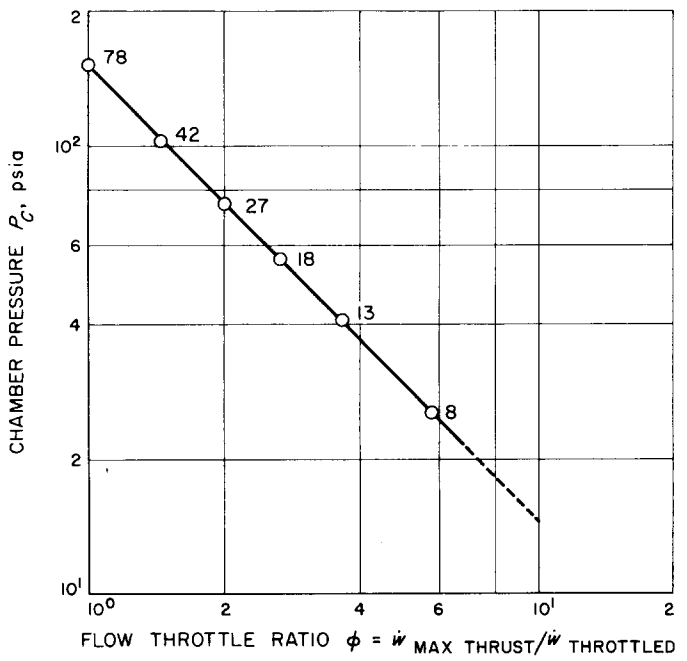

Fig. 3. Variation of chamber pressure with flow throttle ratio

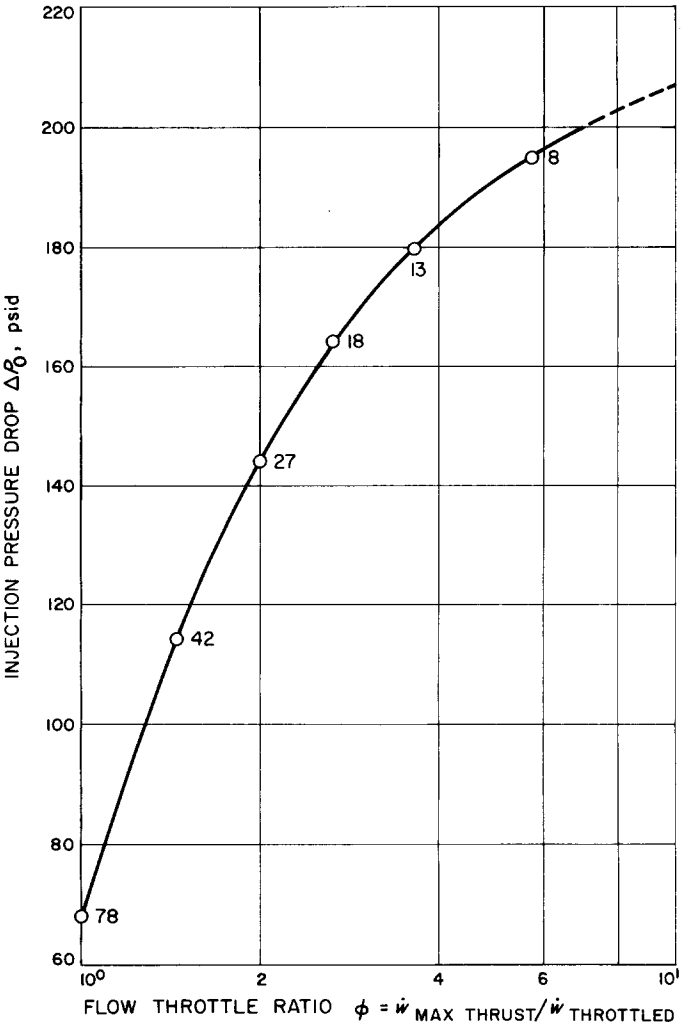

Fig. 4. Variation of pressure drop across injector with flow throttle ratio

Another advantage of this throttling technique is that both the on-off and intermediate throttling functions can be accomplished at constant supply pressure (without pressure-throttling) with a single valve package. This could eliminate the heavy and voluminous manifolding currently required by alternative schemes by feeding each injection element directly.

Apparently, impinging-sheet elements are so inherently efficient that they do not materially depend on interactions with neighboring elements to achieve high

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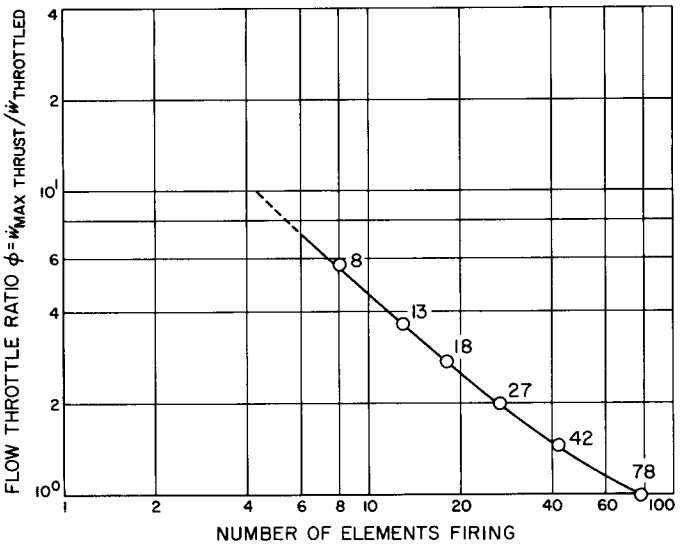

Fig. 5. Throttle ratio as a function of the number of elements firing

performance. This is borne out by the high performance levels realized with only eight widely-separated elements firing (Fig. 1f). Also, combustion instability was not encountered at any time during these throttling experiments, even when the hump-type mass distribution was completely destroyed by progressively turning off elements. It would seem, then, that neither a uniform nor a hump-type mass distribution is absolutely necessary to efficient, stable combustion for a throttlable impinging-sheet injector for N_2O_4/N_2H_4.

Among the disadvantages of discrete-element throttling must be included the fact that flow rate, chamber pressure, and thrust will vary in discrete steps during continuous throttling. Although the points in Fig. 2 have been connected with continuous lines to indicate the consistency of the data, the plots of these parameters during actual discrete-element throttling would consist of a number of isolated points, not related by a continuous function, corresponding to the opening (or closing) of each new group of orifices by the throttle valve. With a very large number of elements, of course, continuous curves would be approached in the limit. Such is nearly the case with the present injector, even when the elements are shut off in groups of five. However, it is easy to envision injectors with very few elements, each contributing a large fraction of the total thrust, where the separation between points might be so wide that discrete-element throttling would probably not be competitive with other techniques.

Finally, in the absence of integral propellant manifolds, injector cooling may prove to be somewhat more difficult, so that this throttling method may be most suitable for shorter-duration firings where heat-sink hardware can be used. It should also be pointed out that in any throttling scheme which involves completely shutting off a number of elements, care must be taken to prevent the accumulation of unreacted propellants in the manifolding or orifice supply tubes.

6. Concluding Remarks

The work to date has demonstrated both (1) the feasibility of using impinging-sheet injection elements and their superiority to more conventional types in terms of performance level, and (2) the near-invariance of performance efficiency over wide throttle ranges using two different throttling schemes. Since several other throttling methods remain to be evaluated, the selection of a technique for use on a flight prototype propulsion system has not been discussed at this time. However, the capabilities and limitations of two promising methods have been explored in depth in conjunction with the impinging-sheet element. Sufficient design criteria have been developed to permit a selection between just these two methods, if necessary. In addition, valuable information regarding element configuration, pattern layout, heat transfer, and combustion stability has been generated and incorporated into the design of a flight prototype injector which is currently being fabricated at JPL.

Future work with the present injector will include firings in shorter chambers, the use of different propellant combinations, and the evaluation of at least one more throttling concept.

Reference

1. *Semi-Annual Review of Research and Advanced Development,* Technical Memorandum 33-296, Vol. II, p. 388, Jet Propulsion Laboratory, Pasadena, California, July 31, 1966.

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